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Exploring the source-to-sink residence time of terrestrial pollen deposited offshore Westland, New Zealand

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Abstract

The occurrence of terrestrial palynomorphs in Quaternary marine sedimentary sequences allows for direct land-sea correlations and provides a means for transferring Marine Isotope Stage chronologies to terrestrial records that extend beyond the range of radiocarbon dating. Both of these important applications require an implicit assumption that the lag between pollen release and final deposition on the seafloor – here referred to as source-to-sink residence time – is negligible in relation to the chronological resolution of the sedimentary sequence. Most studies implicitly assume zero lag, and where studies do take palynomorph residence time into account, its magnitude is rarely quantified. In Westland, New Zealand, fluvial transport is the main source of delivery of terrestrial pollen offshore to the adjacent East Tasman Sea. We radiocarbon dated organic matter carried and deposited by contemporary Westland rivers that drain catchments with varying degrees of disturbance. The ages obtained ranged widely from essentially modern (i.e., -57 ± 22 cal yr BP) to 3583±188 cal yr BP, suggesting that precisely constraining the residence time in this region is unlikely to be achieved in this region. We also compared the timing of four palynomorph events characterising Westland's late Pleistocene, along with the well-dated

Kawakawa/Oruanui Tephra (KOT), between marine core MD06-2991 and four terrestrial records from Westland. Critically, all palynomorph events and the KOT are chronologically indistinguishable with respect to the independently dated marine and terrestrial records, supporting the general principle of transferring the marine chronology onto the terrestrial records in this setting. In other regions, particularly those lacking the high soil production and erosion rates that characterise Westland, we suggest that similar tests of marine residence time should be conducted before assumptions of zero or negligible lag are invoked.

KEYWORDS: pollen residence time; land-sea correlation; Westland; New Zealand; Late Pleistocene

1. Introduction

Terrestrial pollen and spores (palynomorphs) preserved in marine sediments add two useful attributes to the Quaternary scientist's toolkit. First, marine palynomorph records generally provide longer, more continuous archives of vegetation change than records recovered from terrestrial sites. Second, by identifying distinct palynomorph events common to both marine and terrestrial records, there is an opportunity to transfer the well-established Marine Isotope Stage chronology to sections of terrestrial records beyond the range of ^{14}C dating. By placing marine and terrestrial paleoclimate archives on a common timescale, long term ocean and atmosphere interactions can be investigated, offering insights into both key feedbacks and leads and lags within the climate system (Tzedakis et al., 2004; Sánchez Goñi, et al., 2013).

Although records of terrestrial palynomorphs from marine sequences possess clear advantages, the methodology is not without caveats. Palynomorphs deposited offshore have a complex transport history, via soil erosion, river entrainment and ocean currents, potentially resulting in a lengthy lag before final deposition on the ocean floor (Mudie and McCarthy, 1994; McGlone, 2001; Dupont and Wyputta., 2003; van der Kaars and De Deckker, 2003). Taphonomic processes, which are poorly understood compared to terrestrial realm counterparts, may alter how well the relative abundance of palynomorphs in marine records represent their parent plant communities, making these records difficult to interpret in terms of vegetation change (Wilmshurst et al., 1999; Wilmshurst and McGlone, 2005). Indeed, while this uncertainty is often mentioned in the literature, the time from initial palynomorph release to final deposition within a marine sequence is assumed to be negligible. However, the validity of this assumption is rarely tested (Heusser and van de Geer, 1994; Moss et al., 2005). Long residence times would significantly undermine the key objectives of marine-terrestrial comparisons.

In light of this, we investigate the residence time (RT) for palynomorphs terrestrially-derived from Westland, New Zealand (Fig. 1) then delivered to the adjacent Tasman Sea. RT is defined as the total source-to-sink time for a terrestrial palynomorph to travel from its source plant to its final destination on the seafloor. We build on previous work in this region that shows most of the terrestrially-derived palynomorphs recovered from marine sediment cores in the East Tasman Sea have been transported by rivers draining the adjacent Westland region (Ryan et al., 2012). In this study, we explore RT in Westland by two independent methods. First, we attempt to constrain the fluvially-transported component of RT through direct ^{14}C age determinations of palynomorph concentrates and organic residues sampled from contemporary Westland rivers. Second, to assess overall source-to-sink residence time, we compare the relative timing of regionally discernible and independently-dated palynomorph events, and of a widespread tephra marker common to both the marine and terrestrial records. Our ultimate goal is to assess the validity of comparing marine and terrestrial palynomorph records in the time domain at a location where excellent, high-resolution examples of both exist.

2. Study region

Investigating RT in this region, requires an appreciation of the immense productive and erosive capacities of Westland's terrestrial environment as well as an understanding of the East Tasman Sea's submarine canyon system. It is also necessary to briefly summarise Westland's regional vegetation succession previously reported from Last Glacial-Interglacial Transition (LGIT) palynological records. These records provide the basis for evaluating the timing of equivalent events seen in the marine record.

2.1. Terrestrial environment

Westland catchments (Fig. 1) are humid, tectonically active and have high relief, encouraging extremely short palynomorph residence times. Climate is temperate, with mean annual, mean monthly maximum, and mean monthly minimum air temperatures at the coastal town of Hokitika reaching 11.7, 15.7 and 7.7°C, respectively (NIWA, 2014a). Temperature decreases with altitude at a mean rate of ~5.6°C km^{-1}, so that mean annual temperature is 4.1°C at ~1400 masl (metres above sea level), ranging from 7.1°C (Feb) to 0°C (Jul) (NIWA, 2014b). Rainfall is influenced by the adjacent East Tasman Sea and southern mid-latitude westerly winds. The predominantly warm westerly airflow gathers moisture across the Tasman Sea and is orographically forced over the Southern Alps, producing high rainfall in coastal regions (~2900 mm yr^{-1}, Hokitika, 39 masl) (NIWA, 2014b) and extreme rainfall at altitude (11,200 mm yr^{-1}, Cropp, 902 masl) (Hicks et al., 2011). This results in numerous perennial rivers (Fig. 1), high catchment erosion rates (32,000 t km^{-2} yr^{-1}) (Hicks et al., 2011), and soil production and weathering rates ranking among the fastest in the world (2.5 to 12 mm yr^{-1}) (Larsen et al., 2014). In south Westland, four rivers (Arawata, Hokitika, Haast, Whataroa) each deliver ~5-7 Mt yr^{-1} of sediment onto the continental margin of the East Tasman Sea (Hicks et al., 2011).

2.2. Marine environment

The submarine canyon systems of the East Tasman Sea act as an efficient conduit for the large volumes of sediment and organic carbon that are eroded off the Southern Alps and deposited in the deep ocean (Neil, 2008; Hicks et al., 2011; Larsen et al., 2014). Prominent, highly sinuous submarine channel systems incise the relatively steep (0.3-0.5°), narrow (12-50 km) continental shelf and extend >1600 km across the Challenger Plateau (Fig. 1). Down-canyon transport occurs via dense hyperpycnal underflows and rapid submarine gravity flows (Bradford-Greive et al., 2006; Radford, 2012), with a portion of the resulting fine material accumulating on levee banks (Peckall et al., 2000; Proust et al., 2006). Sediment can also be delivered by low-density hypopycnal overflows, identifiable up to 75 km offshore (Moore and Murdoch, 1993).

Terrigenous sediment is also carried northwards by longshore drift. These sediments can be diverted into the Hokitika and Cook submarine canyons at major promontories along the shoreline (Fig. 1) (Norris, 1978; Radford 2012). The largest of these, a paleo-headland, referred to as the 'seaward bulge' by Norris et al. (1978), occurs directly south of the Hokitika submarine canyon head.

High rates of soil production and erosion, in conjunction with longshore drift and a predominantly westerly wind direction, result in palynomorphs that are deposited offshore primarily by fluvial routes (Ryan et al., 2012). However, taphonomic processes affect palynomorphs during fluvial and marine transport. In marine sediments, taxa with more robust, non-anemophilous (i.e., not wind-pollinated) palynomorphs, such as Asteraceae and *Cyathea* spp., often appear in greater relative abundance than in terrestrial depositional settings (Crouch et al., 2010; Mildenhall and Orpin 2010; Ryan et al., 2012). Conversely, central-south Westland terrestrial records contain a wider array of palynomorphs, including some taxa that deteriorate beyond recognition during offshore transport (e.g., Newnham et al., 2013; Vandergoes et al., 2013a). These differences in pollen taphonomy between marine and terrestrial depositional settings can therefore result in selective biases that must be taken into account when direct comparisons are made between the two domains.

2.3. Westland's late Pleistocene palynomorph sequence

Pollen profiles generated from Westland lake sediments depict a regional vegetation succession over the LGIT. A shrubland-grassland mosaic, with patches of southern beech and rare conifers, progressed into a mix of shrubs and conifers and then finally into a landscape dominated by tall conifer trees (Moar and Suggate 1996; Newnham et al., 2007a; Newnham et al., 2012; Vandergoes et al., 2013a). Palynologically, this sequence can be divided into four zones: 1) initially high proportions of Poaceae pollen (occasionally Asteraceae), followed by successively increasing proportions of *Coprosma* and *Myrsine* (occasionally *Halocarpus*); 2) then increasing tree ferns and the conifer species *Podocarpus*/*Prumnopitys*, maximum *Myrsine* and decreasing *Coprosma*, 3) followed by maximum *Podocarpus*/*Prumnopitys* and tree fern spores; culminating in 4) a high abundance of the tall conifer tree *Dacrydium cupressinum* and decreasing *Podocarpus*/*Prumnopitys*. The regional timing of these palynological zones provides the basis for marine and terrestrial comparisons.

3. Methods

3.1. Radiocarbon dating of fluvially-transported material

3.1.1. Organic fraction sizes

We collected a range of material for radiocarbon dating from eight Westland rivers to assess variability of the fluvially-transported component (Fig. 1; Table 1). Material originated from catchments of differing size and degree of anthropogenic impact and comprised both suspended sediments from the water column and riverine silt deposits. Both sample classes were further sub-divided into three organic fraction sizes: macro-organic material (>90 µm), organic material (90> to >45 µm) and palynomorph concentrate (45> to >6 µm) (Table 1) following a variation on separation and concentration methodologies presented in Vandergoes and Prior (2003), Newnham et al. (2007b) and Howarth et al. (2013). This involved using HCl to remove $CaCO_3$ and KOH to remove humic acids; multiple sieving steps (90-6 µm); and organic matter concentration using pre-filtered (1.2 µm) sodium polytungstate (SPT) heavy liquid separation (2.0-1.1 s.g.). These methods were used to both isolate various fractions of organic material and exclude black carbonaceous particulate matter (potentially ^{14}C dead), which was observed in some samples. A subsample of each palynomorph and organic concentrate submitted for radiocarbon analysis was mounted on glass slides with glycerine jelly and inspected with a binocular microscope to determine contents.

3.1.2. Suspended sediment and silt deposit sampling

Suspended sediment samples were collected under baseline (57-64 m^3s^{-1}) (NIWA, 2013) and flood (≥90th percentile of the 2003-2013 flow regime) (NIWA, 2013) conditions between October and November, 2012. During baseline flow, a PVC pipe and socket (50 x 7 cm), fitted with a 15-μm nylon mesh, was pointed upstream to filter and collect material as water passed through. The pipe filled rapidly with water and was tilted upright to drain, then placed back in the river to refill; this process was repeated for 25 minutes, equivalent to filtering ~250 l of water. Some palynomorphs <15 μm were also retained on the 15-μm mesh due to clumping of the organic material. This component was added to the sample collected and subsequently filtered at 6 μm, thereby extending the lower limit of organic fractions sizes from 15 to 6 μm. Suspended sediments were also collected from the Whataroa, Hokitika and Totara Rivers during floods. These samples were used to evaluate whether or not organics eroded and entrained during a flood produced older ^{14}C ages than material transported during base flow. These rivers carry abundant sediment loads during floods, so organic material was able to be concentrated from just five litres of water from each river.

Riverine silt deposits were also collected from Hokitika and Whataroa Rivers, between January and February, 2008, due to concerns, subsequently confirmed, that the waterborne samples may not have sufficient material for ^{14}C dating. These deposits likely represent continuous deposition in the case of Hokitika River and a high discharge event in the case of Whataroa River. The Hokitika River silt deposit was collected between two boulders submerged during low flow, located ~1 km from the river's mouth (Fig. 1). These deposits have accumulated over an unknown time period. The exposed Whataroa riverbed silt, situated adjacent to flowing water, was retrieved following a flood that occurred one day earlier. To limit the amount of aerially transported palynomorphs, the upper 2 cm of the Whataroa silt deposit was removed before sampling.

3.1.3. Radiocarbon dating and numerical methods

All material for this study, including marine core MD06-2991 samples (section 3.2.1), was submitted to the Rafter National Isotope Centre (GNS Science) or Australian Nuclear Science and Technology Organisation (ANSTO) for AMS radiocarbon dating. Radiocarbon ages of terrestrial samples were calibrated in OxCal v4.2.4 (Bronk Ramsey, 2009a) using SHCal13 (Hogg et al., 2013) extended to AD 2012 by the SH Zone 1-2 data (Hua et al., 2013). A principal components analysis (PCA) of the fluvially-transported component was performed to summarise the complex relationships inherent to this data set. The PCA was run in R v3.1.2 (R Core Team, 2014) with the vegan library (Oksanen et al., 2014). Sediment type (1=suspended sediment, 2=riverine silt), flow (1=baseline, 2=variable, 3=flood), organic fraction (1=palynomorph concentrate, 2=organic material, 3=macro-organic material), catchment disturbance and size, river length, carbon content, the abundance of fern spores in each sample, and sample age were all included in the ordination, scaled to unit variance.

3.2. Comparing the timing of key events in marine and terrestrial records

To investigate RT, we compared the timing of palynomorph events characteristic of Westland's late Pleistocene sequence, along with the deposition of the well-studied

Kawakawa/Oruanui Tephra (KOT), between marine core MD06-2991 and four lake sediment records (Fig. 1). These lake sediment records are all proximal to the coast (1.6, 21.6 and 8.2 km = min, max and mean distance from the coast, respectively). Critically, if the timing of events overlaps in all records, within errors of the age-depth models, then RT is negligible, validating the assumption of near-contemporaneous deposition of palynomorphs at terrestrial and adjacent marine sites.

3.2.1. MD06-2991 radiocarbon chronology and recalibration of lake sediment records

Marine sediment core MD06-2991 was retrieved with a Calypso piston corer from the northern levee bank of the Hokitika submarine canyon system (42°21´06´´S, 169°59´59´´E, 886 mbsl) by the R.V Marion Dufresne (Proust et al., 2006). The late Pleistocene portion of the record encompassed the top 2.3 m of the 33 m core.

A chronology was developed from 15 AMS ^{14}C ages (Table 2; Fig. 2); dates were measured on whole mixed planktonic foraminifera tests (~10 mg of $CaCO_3$). The AMS radiocarbon ages were converted to calendar years using the Marine13 calibration curve (Reimer et al., 2013) and a regional reservoir correction (ΔR) of -24 yr (30 s.d.). The regional reservoir correction was estimated by averaging the ΔR of the ten closest locations to the core site from the marine reservoir correction database (http://intcal.qub.ac.uk/calib/), all of which are situated in a similar subtropical water mass. We have assumed that ΔR has remained constant over time. Although ΔR has been shown to vary over the time frame of this study in other situations (e.g. Sikes et al., 2000) we are unable to test this assumption rigorously from available data. However, we note that the age of Kawakawa_Oruanui Tephra determined using our ΔR correction corresponds closely to the established age for the tephra (Fig. 2). Further, we point out that the relatively low temporal resolution of our records means that even potential variations in ΔR of several centuries will not impact our interpretation or conclusions. An age-depth model was generated with OxCal v4.2.4 (Bronk Ramsey 2009a), using a P Sequence model (Bronk Ramsey 2008) with a variable k parameter (Bronk Ramsey and Lee, 2013).

Chronologies for Okarito Bog (Vandergoes et al., 2005; Newnham et al., 2007a), Galway tarn (Vandergoes et al., 2013a,b), Gillespie's Beach Rd (Vandergoes and Fitzsimons, 2003; Turney et al., 2006) and Manks Tarn (Callard, 2011) were remodelled for this study (Suppl Figs. 1-4). Radiocarbon dates were recalibrated to SHCal13 (Hogg et al., 2013) and age-depth models were developed using a P_Sequence model (Bronk Ramsey 2008) with a variable k parameter (Bronk Ramsey and Lee, 2013) in OxCal v4.2.4 (Bronk Ramsey 2009a). The age of the KOT was also remodelled using the Chronological Query Code from Vandergoes et al. (2013b), modified to calibrate radiocarbon ages with SHCal13 (Hogg et al., 2013). The KOT was previously dated to 25,360±162 cal yr BP (2σ) (Vandergoes et al., 2013b: Table S1), whereas the recalibrated age presented here is 25,590±72 cal yr BP (2σ), producing a difference of 230±178 cal yr BP (2σ). This recalculated KOT age was assigned to depth positions within sediment cores retrieved from Galway tarn and Okarito Bog where the KOT tephra correlative was stratigraphically represented.

3.2.2. MD06-2991 palynology

We chose a palynomorph sampling strategy to evenly space samples in time. To accommodate sedimentation rates that varied from 6.7 cm kyr^{-1} to 11.8 cm kyr^{-1}, we collected 26 palynomorph samples at intervals ranging from 2 to 20 cm. This produced a resolution of 1.2 kyr per sample prior to 18 ka and 1.1 kyr thereafter. Palynomorphs were concentrated from 5 to 12 g of dry bulk sediment and mounted on slides following a method modified from Faegri and Iversen (1989). To determine absolute grain abundance, each sample was spiked with an exotic *Lycopodium* marker spore tablet (20,848 grains, s.d 1,546). Samples were digested in 10% HCl to remove $CaCO_3$, disaggregated in hot sodium hexametaphosphate (0.5 g/L) for 30-45 min, and treated with a hot 10% KOH bath (20 min) to remove humic acids. Acetolysis was undertaken (9:1 v/v solution of acetic acid and sulphuric acid) at 96°C for 5 min to remove cellulose. Organic and lithogenic materials were separated using a 2.0 specific gravity (s.g.) sodium-polytungstate heavy liquid. Floated material was washed through a 6 µm wet sieve, retaining the coarse fraction. The resulting residue was lightly stained with safranin to aid identification. Palynomorph identification was made using standard reference texts (Pocknall, 1981a, b; Large and Braggins, 1991; Moar, 1993) and the Victoria University of Wellington, New Zealand, pollen reference collection.

The relative abundance of each taxon was calculated using a total dryland pollen sum that ranged between 334 and 108 grains (mean=256). Dryland pollen were grouped according to the four categories of Vandergoes et al. (2005): podocarp-hardwoods, predominantly comprised of *Dacrydium cupressinum, Prumnopitys ferruginea, Prumnopitys taxifolia, Metrosideros* spp.; southern beech, with Nothofagaceae separated into *Fuscospora* and *Lophozonia* following Heenan and Smissen (2013); montane-subalpine trees and shrubs, including Asteraceae, *Coprosma* spp., *Halocarpus* spp., *Myrsine* spp., *Phyllocladus* spp.; and herbs, primarily Poaceae. The proportions of non-dryland palynomorphs, including tree ferns (*Cyathea* spp.), ferns and fern allies, wetland and exotic pollen (*Casuarina* spp.), were calculated using the method defined by Faegri and Iversen (1989).

Four palynomorph 'events' from MD06-2991 were defined using prominent changes in the abundance, or first or last occurrence of key taxa identified in Westland's late Pleistocene terrestrial records (suppl. Figs 5-8). These pollen events are generally characteristic of Westland's palynostratigraphy and are documented widely in regional palynological and paleovegetation reconstructions (such as Moar 1973, McGlone et al. 1995; Vandergoes & Fitzsimons 2003; Vandergoes et al 2013). To help visualise palynomorph trends, a detrended correspondence analysis (DCA), with rare taxa down-weighted, was undertaken using the vegan library (Oksanen et al., 2013) in R (R Core Team, 2014). Palynomorph profiles were also independently zoned with stratigraphically constrained cluster analysis (CONISS), using a square-root transformation performed for all dryland pollen taxa and the relative abundance of tree ferns, excluding values <2% (Grimm, 1987).

3.2.3. Kawakawa/Oruanui Tephra (KOT) in MD06-2991 and onshore correlatives

We compared the geochemical fingerprinting of cryptic volcanic glass in marine core MD06-2991 to terrestrial Westland records containing the KOT, including: Okarito Bog, Galway tarn, and other New Zealand sites (Fig. 3). This tephra layer provides an isochronous marker independent of the MD06-2991 radiocarbon chronology (Pillans et al., 1993; Lowe et al., 2008; Vandergoes et al., 2013b).

Glass shards from 180.5-181 centimetres below surface (cmbsf) were separated with 2.0 s.g. sodium-polytungstate. The separated fraction was sieved through 63 µm meshes with glass shards analysed for major elements using a JEOL Superprobe (JXA-8230), housed at Victoria University of Wellington, and corrected using the ZAF method. Analyses were performed using an accelerating voltage of 15 kV under a static electron beam operating at 8 nA. The electron beam was defocused to yield a spot size between 10 and 20 µm. The abundance of all elements was calculated on a water-free basis, with H_2O by difference from 100%. Total Fe was expressed as FeO_t and all samples were normalised against glass standards ATHO-G (Jochum et al., 2000) and/or VG-568 (Jarosewich et al., 1980). The accuracy of maximum shard concentration was compared to our recalibrated terrestrial age of the KOT.

4. Results

4.1. Radiocarbon dating of fluvially-transported material

The ages of pollen samples collected from suspended and deposited sediment in modern rivers range from instantaneous (-57±22 cal yr BP to 3583±188 cal yr BP (Table 1). Unfortunately, base flow suspended sediment sampling of individual rivers did not yield enough material to radiocarbon date, so the base flow samples from all rivers were amalgamated before submission. As these amalgamated samples were of mixed origins, we left them out of the PCA. The first two axes of the PCA together explain 66% of the variance in the modern radiocarbon data set Fig. 4). Principal component (PC) 1, explaining 42% of the variance, is positively associated with catchment size, river length and amount of carbon combusted and negatively associated with flow. PC2, explaining 24% of the variance, is positively related to age of the sample and fern spore content and negatively related to the organic fraction size (i.e., macro-organic material, organic material, and palynomorph concentrate).

4.2. Comparing the timing of key events in marine and terrestrial records

The upper 2.3 m of MD06-2991 consists of greenish-grey, foraminifera-rich muds, with iron staining in the uppermost 8 cm. One radiocarbon date, at 105-105.5 cmbsf, is identified as an outlier (Table 1). However, weighting that date as an outlier produced an acceptable agreement of 65% and an overall agreement index for the model (A_{model}) of 102%. The resulting age-depth model possesses a fairly uniform sedimentation rate, despite a slowdown after roughly 18 cal kyr BP (Fig. 2).

MD06-2991 preserves a Westland palynomorph succession with salient features clearly recognisable from nearby terrestrial sites. The Last Glacial Cold Period (Newnham et al., 2007c) is characterised by the highest percentages of Poaceae and herbs for the entire record and abundant *Coprosma* and Asteraceae (Fig. 5). The first palynomorph zone, characterised by maximum *Coprosma*, high abundances of Poaceae and herbs, and increasing *Myrsine*, occurs between 18.2 and 17.7 cal kyr BP (Fig. 5). The second zone, characterised by increasing podocarp-hardwoods, maximum *Myrsine* and decreasing *Coprosma*, occurs between 17.3 and 16 cal kyr BP (Fig. 5). Maximum *Podocarpus*/*Prumnopitys* and tree fern spores appear around 12.1 to11.6 cal kyr BP, the third zone (Fig. 5). Finally, the fourth zone, denoted by increasing *Dacrydium cupressinum* and decreasing *Podocarpus*/*Prumnopitys*, occurs between 11.9 and 9.8 cal kyr BP (Fig 5). Critically, the palynomorph events of MD06-2991 coincide with the 95% confidence limit of the same, independently dated events for the four lake sediment records (Fig. 6): Okarito Bog, Galway tarn, Gillespie's Beach Rd and Manks Tarn (see Suppl Fig. 5,6,7,8 for respective palynostratigraphies).

The maximum density of volcanic glass shards in MD06-2991 appears at 200.5-201 cm, corresponding to 25,140±786 cal yr BP (2σ) based on the age-depth model (Fig. 2, Inset B). The recalibrated eruption age for the KOT is 25,589±72 cal yr BP (2σ), which is statistically indistinguishable within error, from the independently calculated age for maximum KOT glass shard concentration in MD06-2991.

5. Discussion

In this study, we set out to investigate RT, the time taken for a terrestrial palynomorph to be transported from its source plant to its final destination on the east Tasman seafloor. Evaluating this potential lag is crucial where palynostratigraphies from marine archives are either compared to terrestrial counterparts or used to transfer marine chronologies to land-based proxies (e.g., Moss et al., 2007; Ryan et al., 2012).

In the Westland region, the most important component of RT is likely to be fluvial transport to the marine environment. Traditional Quaternary techniques permit an approximation of this component, by radiocarbon dating material entrained by rivers, and of RT overall, by comparing the timing of stratigraphic events from lakes near the ocean to those same events archived in a marine core.

5.1. Radiocarbon dating of fluvially-transported component

In the PCA results (Fig. 4), PC1 reflects our diverse sampling regime – disturbed and undisturbed catchments, long and short river lengths, variable and high flow rates, and samples with differing amounts of carbon. However, PC2 provides insight with respect to varying residence time. Older samples (>0 on PC2) tend to consist of smaller size organic fractions (pollen concentrates and micro-organic material), and samples with high fern spore abundance.

Previous studies highlight the comparatively high concentrations of robust tree fern spores, relative to dryland pollen taxa, in reworked sediments, for instance during glacial retreat (Newnham et al., 2007a) and by fluvial-driven erosion of catchment soils (Dunbar et al., 1997, Wilmshurst et al., 1999). Recent radiocarbon dating from soil profiles in Westland by Howarth et al. (2013) shows that fern spores are preferentially preserved relative to dryland pollen taxa and samples dominated by fern spores may produce ages significantly older than other material from the same horizon. Black carbonaceous particulate matter (potentially ^{14}C dead) found in some samples in the current study when inspected with the binocular microscope are another source of older carbon.

The broad range of ages determined from the riverine samples are likely to reflect these sources of older carbon, reworked into the riverine sediments in the modern anthropogenically-disturbed Westland environment and possibly accentuated by the small sample size (Table 1). The results of this part of the study therefore are inconclusive in terms of constraining the fluvial delivery component of RT in Westland. Clearly some riverborne sediment is delivered to the coast in the modern setting with negligible lag, but not all.

5.2. Comparing the timing of key events in marine and terrestrial records

There is clear synchronicity between MD06-2991 and comparable terrestrial records, with respect to the four palynomorph events and KOT (Fig. 6). Considering three of the four terrestrial sites are small and lack significant tributaries, the spatially diverse, though temporally indistinguishable signals, are convincing evidence that the RT is negligible for Westland. This synchronicity persists throughout both the Last Glacial Cold Period (LGCP; Alloway et al., 2007), when deposition rates of terrigenous material on the levees of the Hokitika and Haast canyons were almost double (Radford, 2012; Nelson et al., 2013), and the LGIT. During this latter period, global sea level rose from 120 to 95 m below present (Carter et al., 1986; Rohling et al., 2009), corresponding to a shoreline migration ~10 km landwards on gentler slopes (Radford, 2012). At the same time, regional climate also warmed substantially to interglacial values, causing glaciers to shrink and allowing vegetation to recolonise the region. Despite major environmental changes, RT remained negligible.

It is important to note that the palynomorph events used to compare marine and terrestrial records are based on trends rather than magnitude. While these marine and terrestrial records are similar, they also possess distinct differences related to taphonomic processes. For instance, terrestrial sites record higher relative abundances of anemophilous Poaceae pollen, which are less durable than other palynomorphs and degrade during fluvial and marine transport. Conversely, comparatively high abundances of entomophilous palynomorphs, like Asteraceae pollen, are recorded in marine sediments, which is attributed to the robustness of the pollen grain. Furthermore, Events 3 and 4 are reversed at Gillespie’s

Beach Rd (Fig. 6, Suppl Fig. 7). Gillespie's Beach Rd possesses poor drainage conditions due to its location within sloping LGCP recessional moraines (Vandergoes and Fitzsimons, 2003; Turney et al., 2006). Consequently, the appearance of *Dacrydium cupressinum* before *Podocarpus*/*Prumnopitys* most likely reflects a local signal, as *D. cupressinum* can better tolerate boggy substrates (Norton et al., 1988).

5.3. The Kawakawa/Oruanui Tephra

The KOT, which erupted from the central North Island of New Zealand over a short duration of weeks to months, provides an independent chronological link between marine and terrestrial sequences (Pillans et al., 1993; Carter et al., 1995; Wilson, 2001; Manville and Wilson, 2006; Vandergoes et al., 2013b). The delivery of the KOT to MD06-2991 likely followed similar pathways as terrestrial palynomorphs. After airborne deposition, the tephra would have been eroded off the adjacent landscape and delivered to the ocean via the paleo Hokitika, Totara and Waitaha Rivers (Norris, 1978). The age of deposition at Okarito Bog and Galway tarn, where it is clearly an airfall deposit is statistically indistinguishable from the independently-dated horizon of highest shard concentration in MD06-2991. This provides further evidence that RT is less than the resolving power of our sedimentary records (i.e. a few hundred years), supporting both the comparison of marine and terrestrial palynomorph records and the transfer of marine chronologies to adjacent terrestrial settings.

6. Conclusions

We attempted to constrain RT, namely the source-to-sink time for terrestrial palynomorphs to reach the ocean floor in Westland, New Zealand. By radiocarbon dating fluvially-transported material, a critical component of RT, we determined that component ranged from being nearly instantaneous to lagging 3583±188 cal yr BP in this anthropogenic setting, characterised by high rates of erosion. On the other hand, the synchronicity between MD06-2991 and four Westland archives, with respect to deposition of the KOT and regional palynomorph events, indicates that RT overall is negligible for Westland. We conclude that 1) terrestrial palynomorphs, deposited alongside marine proxies in MD06-2991, enable direct ocean-land comparisons to be confidently made, even over periods of major environmental change; and 2) the terrestrial palynomorph record of MD06-2991 can be used to transfer its independently derived $\delta^{18}O$ chronology to terrestrial sequences in Westland, beyond the period datable by radiocarbon, by alignment of palynomorph events common to both records. Nevertheless, radiocarbon ages of up to 3.5 ka for recent fluvially-transported material in disturbed catchments provide a warning that RT in some settings has the potential to be much greater and we suggest that similar tests of terrestrial-marine RT should be conducted before assumptions of zero or negligible lag are invoked.

7. Acknowledgements

We acknowledge the officers and crew from the R.V. Marion Dufresne MATACORE 152 cruise for the collection of the MD06-2991 core used in this study. We thank Christopher Bronk Ramsey for his advice on OxCal v4.2.4. Support for this research came from the Australian Institute of Nuclear Science and Engineering (AINSE) Award No's ALNGRA1116 and ALNGRA10524. Radiocarbon dates on the MD06-2991 core were also funded by NIWA core funding under Marine Physical Resources and Processes Programme. M.T. Ryan was funded through Victoria University of Wellington and GNS Global Change with Time programme (540GCT41). Stage flow data for the Arawata, Haast and Hokitika sites was funded by NIWA under the Environmental Information Research Programme 1 (2013/14 SCI). Stage flow data for the Whataroa River was funded by NIWA, Meridian

Energy and NZX. The manuscript benefited from constructive comments by Dr. Bill McLea, Dr. Christine Prior, Professor Euan Smith, and Dr. Katie Collins.

8. References

Alloway B.V., Lowe DJ, Barrell D.J.A., Newnham, R.M., Almond P.C., Augustinus P.C., Bertler N.A.N., Carter, L.C., Litchfield L.C., McGlone M.S., Shulmeister J., Vandergoes M.J., Williams P.W., and NZ-INTIMATE Members, 2007. Towards a climate event stratigraphy for New Zealand over the past 30,000 years. Journal of Quaternary Science 22, 9-35.

Bradford-Grieve, J.M., Probert, K.P., Lewis, K.B., Sutton, P., Zeldis, J., Orpin, A.R., 2006. New Zealand shelf region (31, S). In Robinson, A. R., Brink, K. (Eds.) The Sea, Volume 14B. The Global Ocean: Interdisciplinary Regional Studies and Synthesis. Harvard University Press, Cambridge, MA, pp. 1451-1492.

Bronk Ramsey, C., 2008. Deposition models for chronological records. Quaternary Science Reviews 27, 42-60.

Bronk Ramsey, C, 2009a. Bayesian analysis of radiocarbon dates. Radiocarbon 51, 337-360.

Bronk Ramsey, C., 2009b. Dealing with outliers and offsets in radiocarbon dating. Radiocarbon 51, 1023-1045.

Bronk Ramsey, C., Lee, S., 2013. Recent and planned developments of the program OxCal. Radiocarbon 55, 720-730.

Callard, S.L., 2011. The Last Glacial Maximum and deglaciation in southern New Zealand: new pollen-climate reconstructions. Victoria University of Wellington. Unpublished PhD thesis.

Carter, R.M., Carter, L., Johnson, D.P., 1986. Submergent shorelines in the SW Pacific; evidence for an episodic post-glacial transgression. Sedimentology 33, 629-649.

Carter, L., Nelson, C.S., Neil, H.L., Froggatt, P.C., 1995. Correlation, dispersal, and preservation of the Kawakawa Tephra and other late Quaternary tephra layers in the Southwest Pacific Ocean. New Zealand Journal of Geology and Geophysics 38, 29-46.

Crouch, E., Mildenhall, D., Neil, H., 2010. Distribution of organic-walled marine and terrestrial palynomorphs in surface sediments, offshore eastern New Zealand. Marine Geology 270, 235-256.

Dunbar, G., McLea, B., Goff, J., 1997. Holocene pollen stratigraphy and sedimentation, Wellington Harbour, New Zealand. New Zealand Journal of Geology and Geophysics 40, 325-334.

Dupont, L., Wyputta, U., 2003. Reconstructing pathways of aeolian pollen transport to the marine sediments along the coastline of SW Africa. Quaternary Science Reviews 22, 157-174.

Faegri, K., Iversen, J., 1989. Textbook of pollen analysis (4th Ed.). Wiley, Chichester.

Grimm, E.C., 1987. CONISS: a FORTRAN 77 program for stratigraphically constrained cluster analysis by the method of incremental sum of squares. Computers & Geosciences 13, 13-35.

Fink, D., Hotchkis, M., Hua, Q., Jacobsen, G., Smith, A.M., Zoppi, U., Child, D., Mifsud, C., van der Gaast, H., Williams, A., Williams, M., 2004. The ANTARES AMS Facility at ANSTO. Nuclear Instruments and Methods in Physics Research B 223-224, 109-115.

Heenan, P.B., Smissen, R.D., 2013. Revised circumscription of *Nothofagus* and recognition of the segregate genera *Fuscospora*, *Lophozonia*, and *Trisyngyne* (Nothofagaceae). Phytotaxa 146, 1-31.

Heusser, L.E., van de Geer, G., 1994. Direct correlation of terrestrial and marine paleoclimate records from four glacial-interglacial cycles; DSDP Site 594, Southwest Pacific Quaternary Science Reviews 13, 273-282.

Hicks, D.M., Shankar, U., McKerchar, A.I., Basher, L., Lynn, I., Page, M., Jessen, M., 2011. Suspended sediment yields from New Zealand rivers. Journal of Hydrology (New Zealand) 50, 81-142.

Hogg, A.G., Hua, Q., Blackwell, P.G., Niu, M., Buck, C.E., Guilderson, T.P., Heaton, T.J., Palmer, J.G., Reimer, P.J., Reimer, R.W., 2013. SHCal13 Southern Hemisphere Calibration, 0–50,000 Years cal BP. Radiocarbon 55, 1889-1903.

Howarth, J.D., Fitzsimons, S.J., Jacobsen, G.E., Vandergoes, M.J., Norris, R.J., 2013. Identifying a reliable target fraction for radiocarbon dating sedimentary records from lakes. Quaternary Geochronology 17, 68-80.

Hua, Q., Barbetti, M., Rakowski, A.Z., 2013. Atmospheric radiocarbon for the period 1950–2010. Radiocarbon 55, 2059-2072.

Jarosewich, E., Nelen, J.A., Norberg, J.A., 1980. Reference samples for electron microprobe analysis. Geostandards Newsletter: The Journal of Geostandards and Geoanalysis 4, 43-47.

Jochum, K.P., Dingwell, D.B., Rocholl, A., Stoll, B., Hofmann, A.W., Becker, S., Besmehn, A., Bessette, D., Dietze, H.-J., Dulski, P., Erzinger, J., Hellebrand, E., Hoppe, P., Horn, I., Janssens, K., Jenner, G.A., Klein, M., McDonough, W.F., Maetz, M., Mezger, K.,Münker, C., Nikogosian, I.K., Pickhardt, C., Raczek, I.,Rhede, D., Seufert, H.M., Simakin, S.G., Sobolev, A.V., Spettel, B., Straub, S., Vincze, L., Wallianos, A.,Weckwerth, G., Weyer, S., Wolf, D., Zimmer, M., 2000. The preparation and preliminary characterisation of eight geological MPI-DING reference glasses for in-situ microanalysis. Geostandards Newsletter: The Journal of Geostandards and Geoanalysis, 24, 87-133.

Large, M.F., Braggins, J.E., 1991. Spore atlas of New Zealand ferns and fern allies. A supplement to the New Zealand Journal of Botany. SIR Publishing, Wellington.

Larsen, I.J., Almond, P.C., Eger, A., Stone, J.O., Montgomery, D.R., Malcolm, B., 2014. Rapid soil production and weathering in the Southern Alps, New Zealand. Science 343, 637-640.

Lowe, D, J., Shane, P.A.R., Alloway B.V. and Newnham, R. ,2008. Fingerprints and age models for widespread New Zealand tephra marker beds erupted since 30,000 years ago as a framework for NZ-INTIMATE. Quaternary Science Reviews 27, 95-126.

Manville, V., Wilson, C.J., 2004. The 26.5 ka Oruanui eruption, New Zealand: A review of the roles of volcanism and climate in the post-eruptive sedimentary response. New Zealand Journal of Geology and Geophysics 47, 525-547

McGlone, M.S., 1995. Lateglacial landscape and vegetation change and the Younger Dryas climatic oscillation in New Zealand. Quaternary Science Reviews 14, 867–881.

McGlone, M.S., 2001. A late Quaternary pollen record from marine core P69, southeastern North Island, New Zealand. New Zealand Journal of Geology and Geophysics 44, 69-77.

Mildenhall, D.C., Orpin, A.R., 2010. Terrestrial palynology from marine cores as an indicator of environmental change for the Waipaoa Sedimentary System and north-eastern New Zealand. Marine Geology 270, 227-234.

Moar, N.T., 1973. Contributions to the Quaternary history of the New Zealand flora 7. Two Aranuian pollen diagrams from the central South Island. New Zealand Journal of Botany 11, 291–304.

Moar, N.T., 1993. Pollen grains of New Zealand dicotyledonous plants: Manaaki Whenua Press Lincoln, Canterbury, New Zealand.

Moar, N.T., Suggate, R.P., 1996. Vegetation history from the Kaihinu (last) interglacial to the present, West Coast, South Island, New Zealand. Quaternary Science Reviews 15, 521-547.

Moore, M., Murdoch, R., 1993. Physical and biological observations of coastal squirts under non upwelling conditions. Journal of Geophysical Research-Oceans 98, 20043-20061.

Moss, P.T., Kershaw, A.P., Grindrod, J., 2005. Pollen transport and deposition in riverine and marine environments within the humid tropics of northeastern Australia. Review of Palaeobotany and Palynology 134, 55-69.

Moss, P.T., Dunbar, G., Dickens, G., Jacobsen, G., 2007. Comparative ages of pollen and foraminifera in the ODP 820 marine core. Paper presented at the 15th Australian Conference on Nuclear and Complementary Techniques of Analysis and 9th Vacuum Society of Australia Congress, 21st-23rd November.

Mudie, P., McCarthy, F.M.G., 1994. Late Quaternary pollen transport processes, western North Atlantic: data from box models, cross-margin and NS transects. Marine Geology 118, 79-105.

Neil, H.L., 2008. Sediment conduits to the deep Tasman: two contrasting large canyons-channel complexes from the West Coast, South Island, New Zealand. Paper presented at the Geological Society of New Zealand, New Zealand Geophysical Society and New Zealand Geochemical & Mineralogical Society Joint Annual Conference, Miscellaneous Publication 124A, Page 234.

Nelson, F.E., Wilson, G.S., Neil, H.L., 2013. Marine magnetic signature of the Last Glacial Maximum and last deglaciation from the Southern Hemisphere mid-latitudes. Marine Geology 346, 246-255.

Newnham, R.M., Vandergoes, M.J., Hendy, C.H., Lowe, D.J., Preusser, F., 2007a. A terrestrial palynological record for the last two glacial cycles from southwestern New Zealand. Quaternary Science Reviews 26, 517-535.

Newnham, R.M., Vandergoes, M.J., Garnett, M.H., Lowe, D.J., Prior, C., Almond, P.C., 2007b. Test of AMS 14C dating of pollen concentrates using tephrochronology. Journal of Quaternary Science 22, 37-51.

Newnham, R.M., Lowe, D.J., Giles, T., Alloway, B.V., 2007c. Vegetation and climate of Auckland, New Zealand, since ca. 32 000 cal. yr ago: support for an extended LGM. Journal of Quaternary Science 22, 517-534.

Newnham, R.M., Vandergoes, M.J., Sikes, E., Carter, L., Wilmhurst, J.M., Lowe, D.J., McGlone, M.S., Sandiford, A., 2012. Does the bipolar seesaw extend to the terrestrial southern mid-latitudes? Quaternary Science Reviews 36, 214-222.

Newnham, R.M., McGlone, M.S., Moar, N.T., Wilmshurst, J.M., Vandergoes, M.J., 2013. The vegetation cover of New Zealand at the Last Glacial Maximum. Quaternary Science Reviews 74, 202-214.

NIWA, 2013. The environmental information browser: New Zealand, Hokitika River flow data (2003-2013). URL http://http://ei.niwa.co.nz/

NIWA, 2014a. The national climate database; New Zealand, Ivory Coast Glacier (2009-2014). URL http://cliflo.niwa.co.nz/doc/terms.html.

NIWA, 2014b. The national climate database; New Zealand, Hokitika Aero site (1981-2014). URL http://cliflo.niwa.co.nz/doc/terms.html.

Norris, R.M., 1978. Late Cenozoic geology of the west coast shelf between Karamea and the Waiho River, South Island, New Zealand, Volume 81. New Zealand Oceanographic Institute.

Norton, D.A., Herbert, J., Beveridge, A.E., 1988. The ecology of *Dacrydium cupressinum*: a review. New Zealand Journal of Botany 26, 37-62.

Oksanen, J., Blanchet, F.G., Kindt, R., Legendre, P., Minchin, P.R., O'Hara, R.B., Simpson, G.L., Solymos, P., Henry, M., Stevens, H., Wagner, H., 2014. vegan: Community Ecology Package. R package version 2.2-0. URL http://CRAN.R-project.org/package=vegan.

Peakall, J., McCaffrey, B., Kneller, B., 2000. A process model for the evolution, morphology, and architecture of sinuous submarine channels. Journal of Sedimentary Research 70, 434-448.

Pillans, B., McGlone, M., Palmer, A., Mildenhall, D., Alloway, B., Berger, G., 1993. The Last Glacial Maximum in central and southern North Island, New Zealand; a paleoenvironmental reconstruction using the Kawakawa Tephra formation as a chronostratigraphic marker. Palaegeography, Palaeoclimatology, Palaeoecology 101, 283-304.

Pocknall, D., 1981a. Pollen morphology of the New Zealand species of *Dacrydium* Solander, *Podocarpus* L'Heritier, and *Dacrycarpus* Endlicher (Podocarpaceae). New Zealand Journal of Botany 19, 67-95.

Pocknall, D., 1981b. Pollen morphology of *Phyllocladus* LC et A. Rich. New Zealand Journal of Botany 19, 259-266.

Proust, J., Lamarche, G., Migeon, S., Neil, H.L., Shipboard-party, 2006. Tectonic and climatic controls on sediment budget. MD152/MATACORE on *R.V. Marion-Dufresne*.

R Core Team, 2014. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL http://www.R-project.org/.

Radford, J., 2012. Shelf-to-canyon sedimentation on the South Westland Continental Margin, Westland, New Zealand. University of Canterbury, Unpublished MSc thesis.

Reimer, P.J., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Ramsey, C.B., Buck, C.E., Cheng, H., Edwards, R.L., Friedrich, M., 2013. IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. Radiocarbon 55, 1869-1887.

Rohling, E., Grant, K., Bolshaw, M., Roberts, A., Siddall, M., Hemleben, C., Kucera, M., 2009. Antarctic temperature and global sea level closely coupled over the past five glacial cycles. Nature Geoscience 2, 500-504.

Ryan, M., Dunbar, G., Vandergoes, M., Neil, H., Hannah, M., Newnham, R., Bostock, H., Alloway, B., 2012. Vegetation and climate in Southern Hemisphere mid-latitudes since 210 ka: new insights from marine and terrestrial pollen records from New Zealand. Quaternary Science Reviews 48, 80-98.

Sánchez Goñi, M.F., Bard, E., Landais, A., Rossignol, L., d'Errico, F., 2013. Air-sea temperature decoupling in western Europe during the last interglacial-glacial transition. Nature Geoscience 6, 837-841.

Sikes, E.L., Samson C.R., Guilderson T.P., Howard W.R., 2000. Old radiocarbon ages in the southwest Pacific Ocean during the last glacial period and deglaciation *Nature* 405, 555-559.

Turney, C.S.M., Kershaw, A.P., Lowe, D.J., van der Kaars, S., Johnston, R., Rule, S., Moss, P., Radke, L., Tibby, J., McGlone, M.S., Wilmshurst, J.M., Vandergoes, M.J., Fitzsimons, S.J., Bryant, C., James, S., Branch, N.P., Cowley, J., Kalin, R.M., Ogle, N., Jacobsen, G., Fifield, L.K., 2006. Climatic variability in the southwest Pacific during the Last Termination (20-10 kyr BP). Quaternary Science Reviews 25, 886-903.

Tzedakis, P., Roucoux, K., De Abreu, L., Shackleton, N., 2004. The duration of forest stages in southern Europe and interglacial climate variability. Science 306, 2231-2235.

van der Kaars, S., De Deckker, P., 2003. Pollen distribution in marine surface sediments offshore Western Australia. Review of Palaeobotany and Palynology 124, 113-129.

Vandergoes, M.J., Fitzsimons, S.J., 2003. The Last Glacial-Interglacial Transition (LGIT) in south Westland, New Zealand: paleoecological insight into mid-latitude Southern Hemisphere climate change. Quaternary Science Reviews 22, 1461-1476.

Vandergoes, M.J., Prior, C.A., 2003. AMS dating of pollen concentrates; a methodological study of late Quaternary sediments from south Westland, New Zealand. Radiocarbon 45, 479-491.

Vandergoes, M.J., Newnham, R.M., Preusser, F., Hendy, C.H., Lowell, T.V., Fitzsimons, S.J., Hogg, A.G., Kasper, H.U., Schlüchter, C., 2005. Regional insolation forcing of late Quaternary climate change in the Southern Hemisphere. Nature 436, 242-245.

Vandergoes, M.J., Newnham, R.M., Denton, G.H., Blaauw, M., Barrell, D.J., 2013a. The anatomy of Last Glacial Maximum climate variations in south Westland, New Zealand, derived from pollen records. Quaternary Science Reviews 74, 215-229.

Vandergoes, M.J., Hogg, A.G., Lowe, D.J., Newnham, R.M., Denton, G.H., Southon, J., Barrell, D.J., Wilson, C.J., McGlone, M.S., Allan, A.S., 2013b. A revised age for the Kawakawa/Oruanui tephra, a key marker for the Last Glacial Maximum in New Zealand. Quaternary Science Reviews 74, 195-201.

Wilmshurst, J.M., Eden, D.N., Froggatt, P.C., 1999. Late Holocene forest disturbance in Gisborne, New Zealand : a comparison of terrestrial and marine pollen records. New Zealand Journal of Botany 37(3), 523-540.

Wilmshurst, J.M., McGlone, M.S., 2005. Origin of pollen and spores in surface lake sediments: comparison of modern palynomorph assemblages in moss cushions, surface soils and surface lake sediments. Review of Palaeobotany and Palynology 136, 1-15.

Wilson, C., 2001. The 26.5 ka Oruanui eruption, New Zealand: an introduction and overview. Journal of Volcanology and Geothermal Research 112, 133-174.

9. Figure captions

Figure 1. Regional setting showing sampling sites and locations referred to in the text. Terrestrial sites include (from south to north): Gillespies Beach Road, Galway tarn, Okarito

bog, and Manks Tarn. Black circles 3 to 11 are sites sampled for ^{14}C material suspended in the river during base-flow conditions. Pink circles are locations sampled for ^{14}C material suspended during floods of the Totara and Hokitika Rivers. Yellow crosses are locations were riverbed silts were sampled for ^{14}C. Annual suspended sediment yields to the central-south Westland coast are denoted at the mouths of the high sediment producing Hokitika and Whataroa Rivers (Hicks, 2011). Howarth et al. (2013)'s soil sample, discussed in the text, is depicted as a red triangle. The digital elevation model is from Land Information NZ (LINZ) digital topographic contours and spot heights (Crown Copyright reserved), with bathymetric data supplied by NIWA.

Figure 2. Age-depth model and stratigraphy for MD06-2991 based on fourteen ^{14}C dates (Table 1). The model was produced in OxCal v4.2.4 using a P_Sequence (Bronk Ramsey 2008), with a variable k (Bronk Ramsey and Lee 2013); the Marine13 calibration curve (Reimer et al., 2013); and a regional reservoir correction (ΔR) of -24 yr (30 s.d.). The resulting model has an agreement (A_{model}) of 102. The 68% (dark blue) and the 95% (light blue) confidence levels are shown. Sample agreement, in parentheses after the ^{14}C date with 1σ error; calendar age likelihoods, illustrated in dark pink (see Inset A for magnified example); and posterior probability density functions, in dark grey (see Inset A for magnified example), are shown. Inset A depicts a magnified profile, where the mean (white circle) and median (vertical line in circle) values are shown. Inset B shows the calculated maximum distribution of glass shards/g in MD06-2991 at 200.5-201 cm (25,142 ± 786 cal BP, 2σ), the recalibrated eruption age of the Kawakawa/Oruanui Ignimbrite (25,589 ±72 cal BP, 2σ) presented here, and the original calibration (25,360 ± 160, 2σ cal BP) (Vandergoes et al., 2013b: Table S1).

Figure 3. Glass shard major element bivariate plots of a) CaO vs FeO (wt %) and b) K_2O vs FeO (wt %) from 180.5-181 cmbsf of MD06-2991 (n=17) compared to five previously published KOT analyses (using the same electron microprobe and under the same analytical conditions and standards). Crosses represent the 2σ error on individual analyses.

Figure 4. Principal components analysis of fluvially-transported radiocarbon data set (Table 1). PC1 reflects the diversity of sampled material, while PC2 represents sample ages. Only loadings (in red) with PC1 or PC2 greater than 0.6 are plotted. Letters represent river (H=Hokitika, T=Totara, W=Whataroa), flow (V=varied, F=Flood), and organic fraction size (M=macro-organic material, O=organic material, P=pollen concentrate).

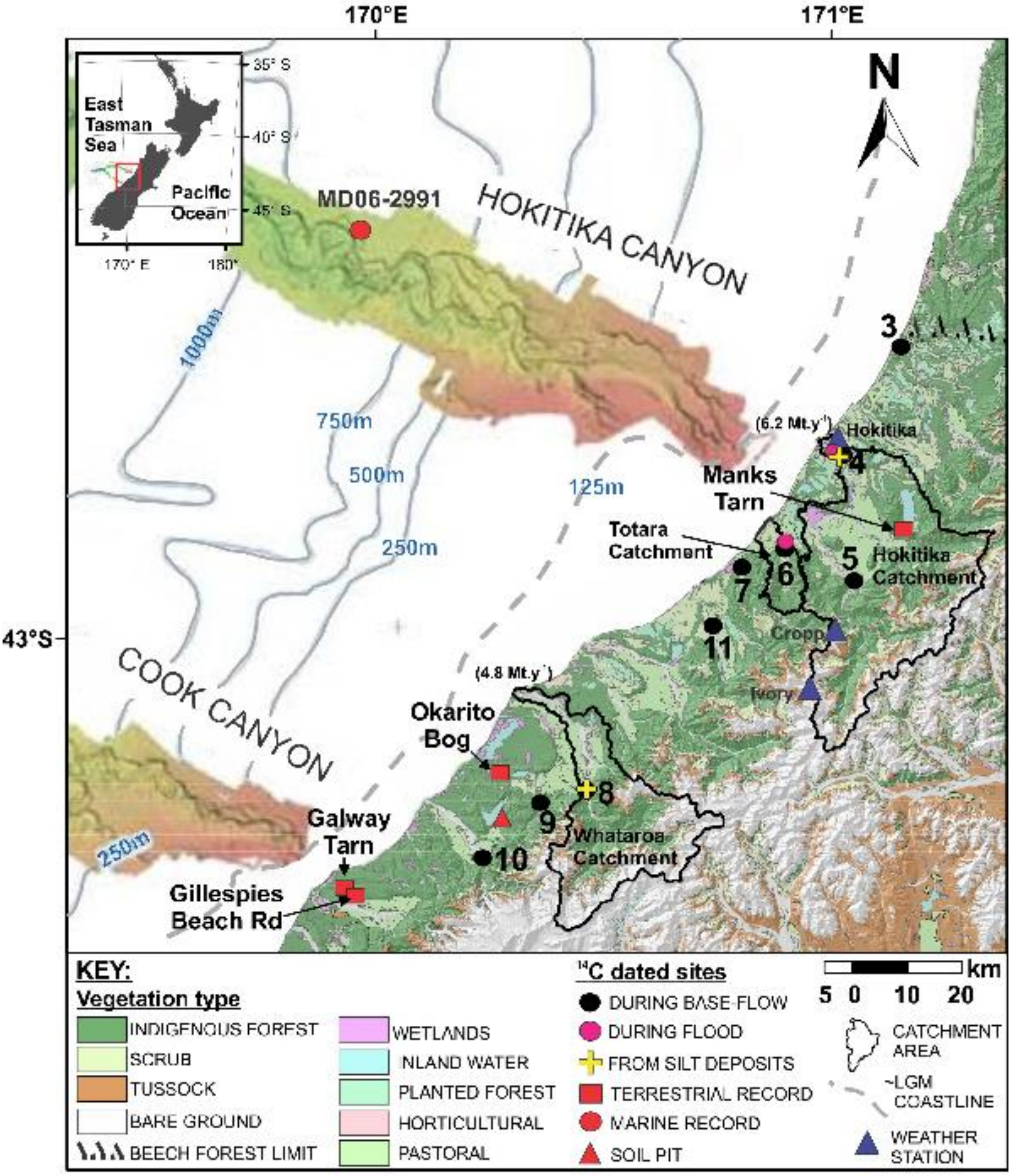
Figure 5. Summary pollen percentage diagram for MD06-2991 and location of key palynomorph events since 30 cal kyr BP. The core stratigraphy and location of the calibrated AMS ^{14}C ages (red triangles) are shown on the left. The relative percentages of the main dryland pollen taxa are shown from left to right and are grouped into a cumulative dryland pollen diagram, which includes podocarp-hardwoods, beech, montane-subalpine trees and shrubs, and herbs. *Podocarpus* (green) and *Prumnopitys* (light green) are displayed grouped, although their respective relative percentages are differentiated by colour and a black line. The proportion of non-degraded *Cyathea* fern spores was calculated following Faegri and Iversen (1989), while the results of DCA axis 1 and the CONISS zonation are presented on the far right. The position of the Kawakawa/Oruanui Tephra (KOT) is shown.

Figure 6. Calibrated calendar year ages (black line) and error range (2σ, dashed line) of the KOT and four palynomorph events in MD06-2991 and their correlatives in Westland terrestrial records. Mean calibrated ^{14}C ages (red triangles) and *R_combine* ages (blue

triangles) are shown next to each record. The weighted mean age and error of each palynomorph event in the terrestrial records are combined to produce a composite stratigraphy next to the MD06-2991. Note, palynomorph event 4 for Gillespie's Beach Rd (GBR) was not included in the composite.

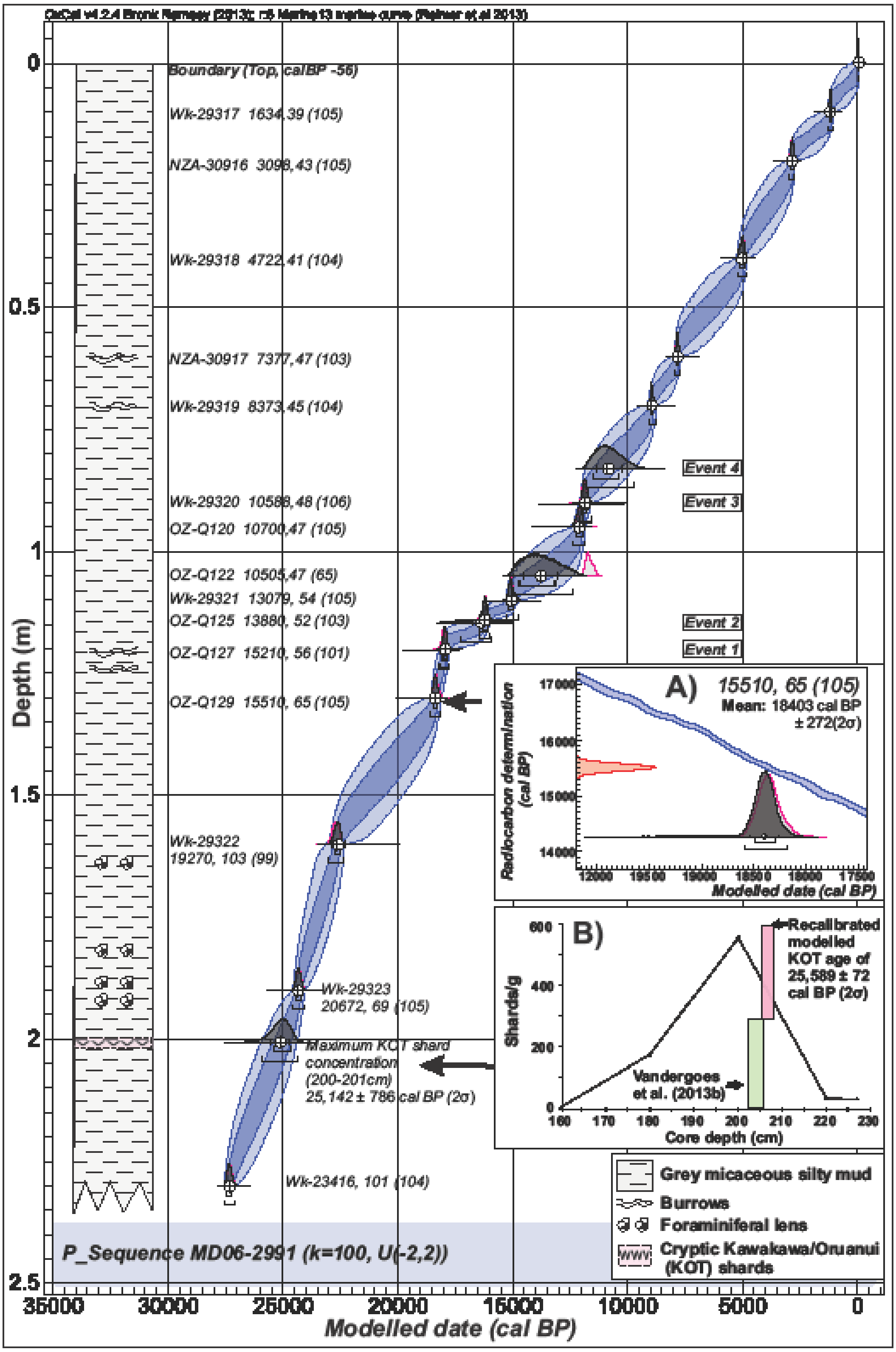
10. Tables

Table 1. Organic material samples collected from Westland rivers submitted for ^{14}C dating (n=14). Samples were submitted to the Rafter National Isotope Centre (GNS Science) and Australian Nuclear Science and Technology Organisation (ANSTO) for radiocarbon dating, and ^{14}C ages were calibrated with SHCal13 (Hogg et al., 2013) in OxCal v4.2.3. Organic residue represents macro-organic residue (MOR), micro-organic matter (OR) and pollen concentrate (PC), with the respective size faction and specific gravity of separation shown. * Indicates an assumed $\delta^{13}C$ value due to limited sample material available for $\delta^{13}C$ determination.



170°E
171°E
43°S
East Tasman Sea
Pacific Ocean
35° S
40° S
45° S
170° E
180°
N
MD06-2991
HOKITIKA CANYON
COOK CANYON
1000m
750m
500m
250m
125m
250m
3
(6.2 Mt.y⁻¹)
Hokitika
4
Manks Tarn
Totara Catchment
6
5
Hokitika Catchment
7
11
Cropp
Ivory
(4.8 Mt.y⁻¹)
Okarito Bog
8
9
Whataroa Catchment
10
Galway Tarn
Gillespies Beach Rd
KEY:
Vegetation type
INDIGENOUS FOREST
SCRUB
TUSSOCK
BARE GROUND
BEECH FOREST LIMIT
WETLANDS
INLAND WATER
PLANTED FOREST
HORTICULTURAL
PASTORAL
¹⁴C dated sites
DURING BASE-FLOW
DURING FLOOD
FROM SILT DEPOSITS
TERRESTRIAL RECORD
MARINE RECORD
SOIL PIT
km
5 0 10 20
CATCHMENT AREA
~LGM COASTLINE
WEATHER STATION

Figure 1



Boundary (Top, calBP -56)
Wk-29317 1634,39 (105)
NZA-30916 3098,43 (105)
Wk-29318 4722,41 (104)
NZA-30917 7377,47 (103)
Wk-29319 8373,45 (104)
Wk-29320 10588,48 (106)
OZ-Q120 10700,47 (105)
OZ-Q122 10505,47 (65)
Wk-29321 13079, 54 (105)
OZ-Q125 13880, 52 (103)
OZ-Q127 15210, 56 (101)
OZ-Q129 15510, 65 (105)
Wk-29322 19270, 103 (99)
Wk-29323 20672, 69 (105)
Maximum KOT shard concentration (200-201cm) 25,142 ± 786 cal BP (2σ)
Wk-23416, 101 (104)
Event 4
Event 3
Event 2
Event 1
Depth (m)
Modelled date (cal BP)
P_Sequence MD06-2991 (k=100, U(-2,2))
A) 15510, 65 (105)
Mean: 18403 cal BP ± 272(2σ)
Radiocarbon determination (cal BP)
B)
Shards/g
Core depth (cm)
Recalibrated modelled KOT age of 25,589 ± 72 cal BP (2σ)
Vandergoes et al. (2013b)
Grey micaceous silty mud
Burrows
Foraminiferal lens
Cryptic Kawakawa/Oruanui (KOT) shards

Figure 2

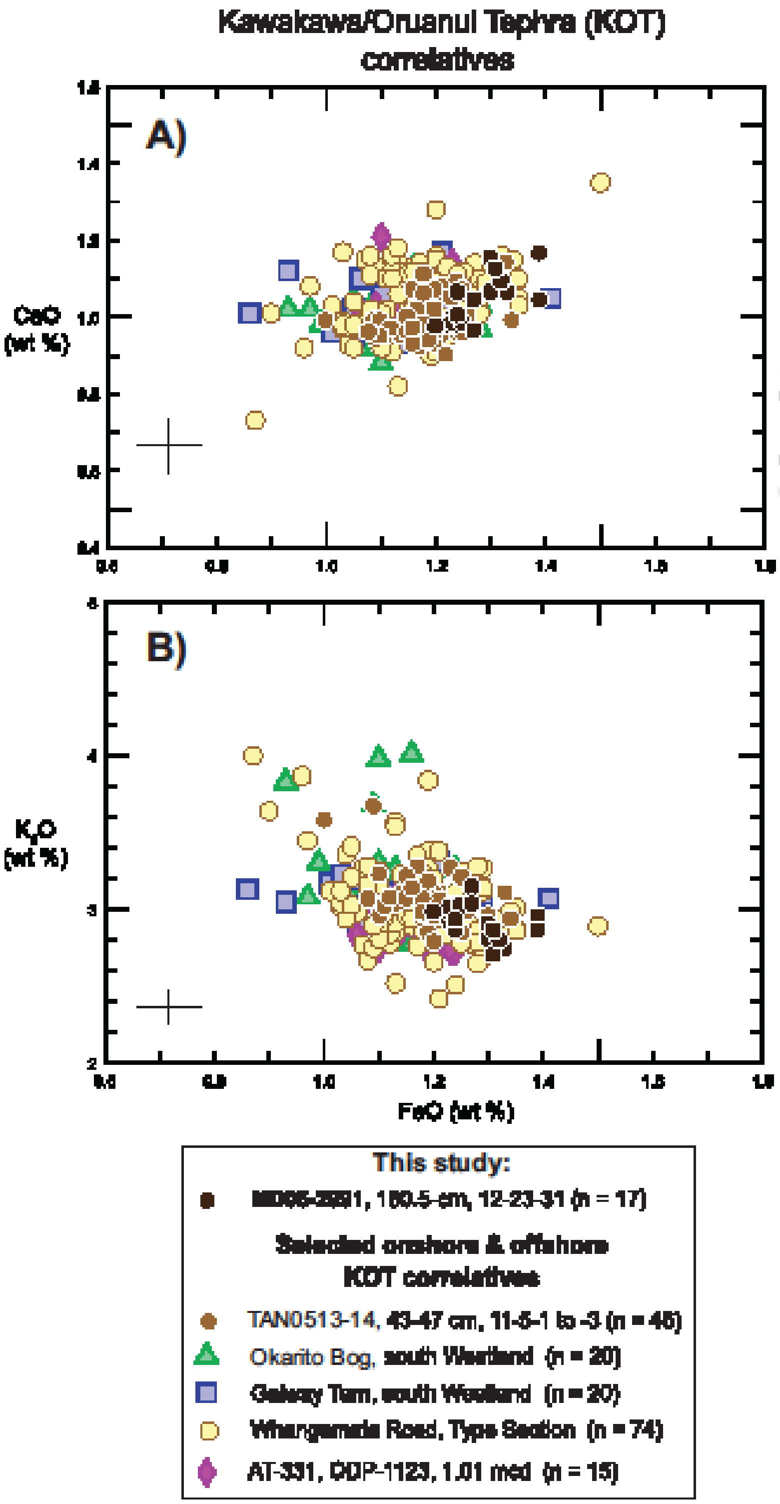
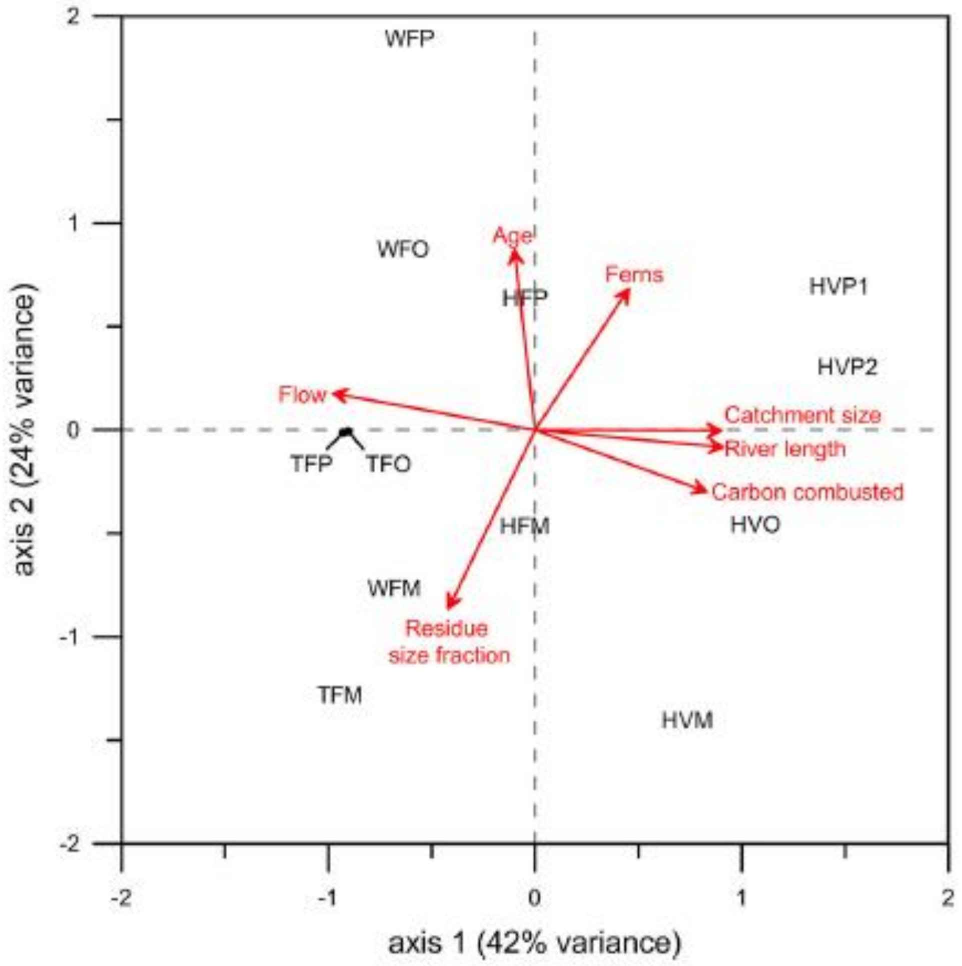

Kawakawa/Oruanui Tephra (KOT) correlatives
A)
CaO (wt %)
B)
K_2O (wt %)
FeO (wt %)
This study:
MD06-2991, 180.5 cm, 12-23-31 (n = 17)
Selected onshore & offshore
KOT correlatives
TAN0513-14, 43-47 cm, 11-5-1 to -3 (n = 46)
Okarito Bog, south Westland (n = 20)
Galway Tarn, south Westland (n = 20)
Whangamata Road, Type Section (n = 74)
AT-331, ODP-1123, 1.01 mcd (n = 15)

Figure 3



axis 2 (24% variance)
axis 1 (42% variance)
2
1
0
-1
-2
-2
-1
0
1
2
WFP
WFO
Age
Ferns
HFP
HVP1
HVP2
Flow
Catchment size
River length
Carbon combusted
TFP
TFO
HFM
HVO
WFM
Residue
size fraction
TFM
HVM

Figure 4

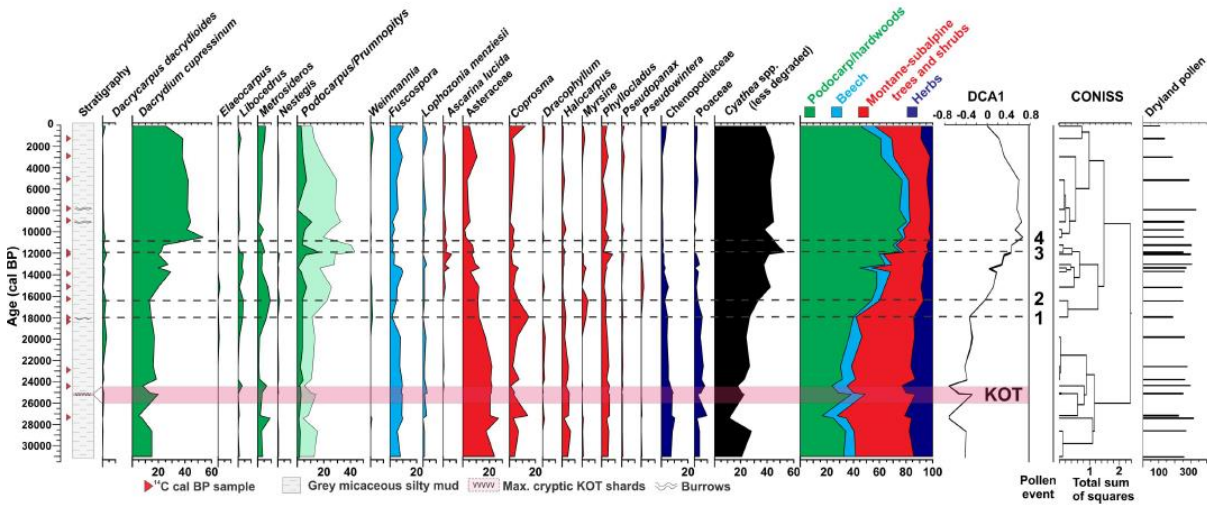
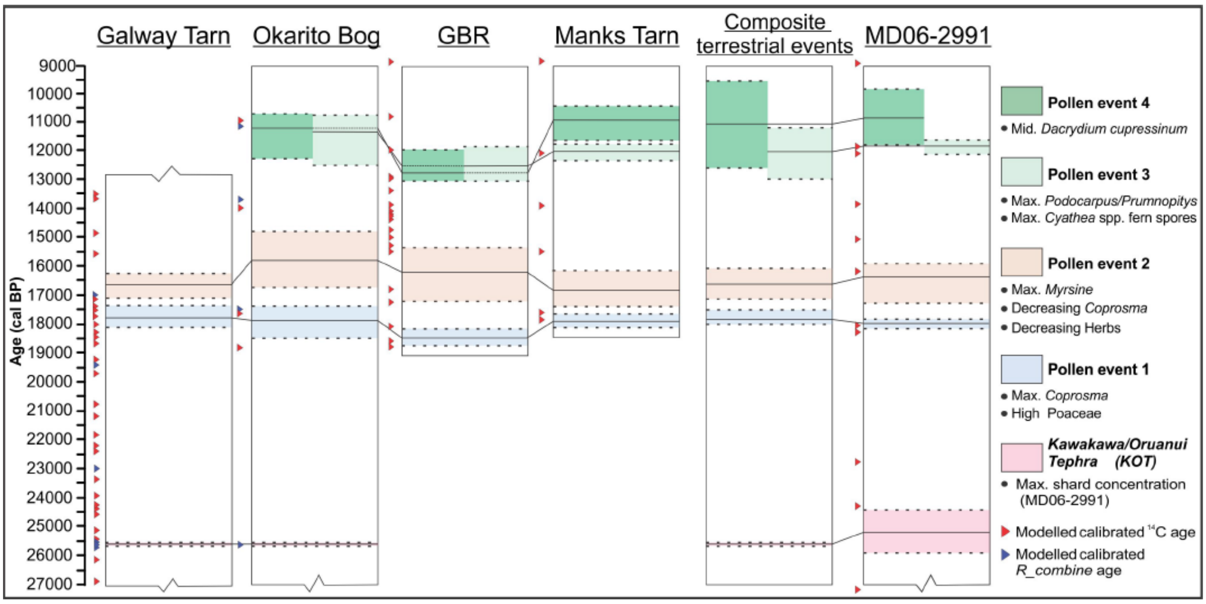

Stratigraphy
Dacrycarpus dacrydioides
Dacrydium cupressinum
Elaeocarpus
Libocedrus
Metrosideros
Nestegis
Podocarpus/Prumnopitys
Weinmannia
Fuscospora
Lophozonia menziesii
Ascarina lucida
Asteraceae
Coprosma
Dracophyllum
Halocarpus
Myrsine
Phyllocladus
Pseudopanax
Pseudowintera
Chenopodiaceae
Poaceae
Cyathea spp. (less degraded)
Podocarp/hardwoods
Beech
Montane-subalpine trees and shrubs
Herbs
DCA1
CONISS
Dryland pollen
Age (cal BP)
KOT
Pollen event
Total sum of squares
¹⁴C cal BP sample
Grey micaceous silty mud
Max. cryptic KOT shards
Burrows

Figure 5



Galway Tarn
Okarito Bog
GBR
Manks Tarn
Composite terrestrial events
MD06-2991
Age (cal BP)
9000
10000
11000
12000
13000
14000
15000
16000
17000
18000
19000
20000
21000
22000
23000
24000
25000
26000
27000
Pollen event 4
Mid. Dacrydium cupressinum
Pollen event 3
Max. Podocarpus/Prumnopitys
Max. Cyathea spp. fern spores
Pollen event 2
Max. Myrsine
Decreasing Coprosma
Decreasing Herbs
Pollen event 1
Max. Coprosma
High Poaceae
Kawakawa/Oruanui Tephra (KOT)
Max. shard concentration (MD06-2991)
Modelled calibrated 14C age
Modelled calibrated R_combine age

Figure 6

Sample	Organic residue	Fraction	Lab code	$\delta^{13}C$ (‰)	pMC ± 1σ	^{14}C age ± 1σ yr BP	Mean age ± 2σ cal. yr BP	Carbon mass (µg)
Suspended sed. base-flow	MOM	x>90 µm, x<2.0 s.g.	NZA55594	-40.3	-	1357 ± 46	1226 ± 102	100
Suspended sed. base-flow	OM/PC	90>x>6 µm, x<2.0 s.g.	NZA55590	-41.1	-	2543 ± 44	2581 ± 188	100
Whataroa silt 'flood' deposit	MOM	x>90 µm, x<1.6 s.g.	NZA55427	-27.1 ± 0.2	105.8 ± 0.24	Modern	-57 ± 22	1000
Whataroa silt 'flood' deposit	OM	90>x>45 µm, x<2.0 s.g.	NZA55592	-37.6	-	1707 ± 35	1577 ± 108	200
Whataroa silt 'flood' deposit	PC	45>x>6 µm, x<2.0 s.g.	NZA55591	-41.7	-	3384 ± 71	3583 ± 188	100
Hokitika silt deposit	MOM	x>90 µm, x<2.2 s.g.	NZA55423	-29.8 ± 0.2	105.8 ± 0.23	Modern	-57 ± 22	1000
Hokitika silt deposit	OM	90>x>45 µm, x<1.4 s.g.	NZA55424	-29.3 ± 0.2	-	658 ± 22	602 ± 54	1300
Hokitika silt deposit	PC	45>x>25 µm, 1.4>x>1.1 s.g.	NZA55425	-29.0 ± 0.2	-	822 ± 19	701 ± 32	1900
Hokitika silt deposit	PC	25>x>6 µm, 1.4>x>1.1s.g.	NZA55426	-29.9 ± 0.2	-	1091 ± 19	948 ± 34	1500
Totara River flood	MOM	x>90 µm, x<2.0 s.g.	NZA55428	-28.2 ± 0.2	104.8 ± 0.25	Modern	-33 ± 54	900
Totara River flood	OM	90>x>50 µm, x<2.2 s.g.	OZO850	-25.0*	-	540 ± 150	495 ± 270	72.9 ± 0.68
Totara River flood	PC/OM	50>x>10 µm, x<2.2 s.g.	OZO851	-28.3	-	645 ± 40	597 ± 66	47.38 ± 0.44
Hokitika River flood	MOM	x>50 µm, x< 2.0 s.g.	NZA55593	-44.5	-	933 ± 35	809 ± 66	200
Hokitika River flood	PC/OM	50>x>10 µm, x<2.2 s.g.	OZO849	-25.0*	-	3240 ± 150	3415 ± 306	150.33 ± 1.4

Table 1

MD06-2991 depth (cmbsf)	Lab number	^{14}C age (yr BP)	± (1σ)	Unmodlled calibrated age (cal BP)	± (2σ)	Modelled calibrated calender age range (cal BP)	± (2σ)
10 – 10.5	Wk-29317	1634	39	1,197	92	1,243	292
20 – 20.5	NZA-30916	3098	43	2,871	122	2,898	228
40 – 40.5	Wk-29318	4772	41	5,041	176	5,085	220
60 – 60.5	NZA-30917	7377	47	7,840	112	7,861	222
70 – 70.5	Wk-29319	8373	45	8,953	150	8,991	312
90 – 90.5	Wk-29320	10588	48	11,873	240	11,862	238
95 – 95.5	OZ-Q120	10700	47	12,106	244	12,168	384
105 – 105.5*	OZ-Q122	10505	47	11,685	300	13,839	1444
110 – 110.5	WK-29321	13079	54	15,072	232	15,149	446
114 – 114.5	OZ-Q125	13880	52	16,219	200	16,272	446
120 – 120.5	OZ-Q127	15210	56	18,010	180	17,969	222
130 – 130.5	OZ-Q129	15510	65	18,356	208	18,443	382
160 – 160.5	NZA-32351	19270	103	22,730	278	22,641	578
190 – 190.5	Wk-29322	20672	69	24,337	230	24,375	298
230 – 230.5	Wk-29323	23416	101	27,337	220	27,352	228

Table 2

Highlights

1. Negligible time lags for pollen transported offshore in this study region.
2. Direct land-sea correlations are viable in this region.
3. MIS chronologies can be transferred to terrestrial records in this region.